Note added December 18.

In addition to the arrangements above described for determining the capacity of the small condenser, we have also employed the well-known method of charging and discharging the small condenser through a galvanometer by means of a contact-maker driven at a speed of sixty contacts per second by an electrically controlled tuning-fork. By this means a steady deflection of the galvanometer is obtained due to the passage of the rapidly recurring discharges through it. Preliminary observations with this apparatus have confirmed the above-given value for the dielectric constant of liquid oxygen, and by a modification of it we hope shortly to make a very careful re-determination of the constant.

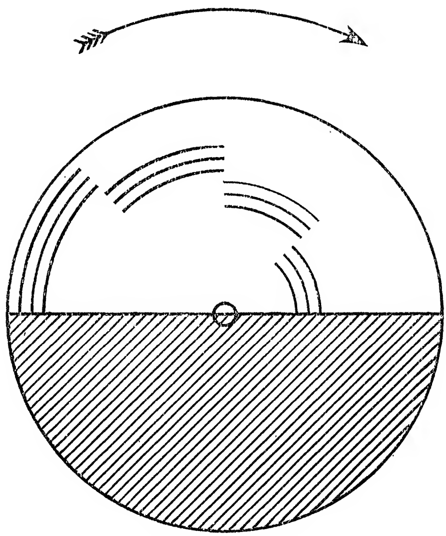
"On Subjective Colour Phenomena attending sudden Changes of Illumination." By SHELFORD BIDWELL, M.A., LL.B., F.R.S. Received December 10,—Read December 17, 1896.

The investigation which forms the subject of this paper originated in an attempt to account satisfactorily for the colour phenomena exhibited by Mr. C. E. Benham's "Artificial Spectrum Top," which, when it was brought before the public, about two years ago, excited considerable interest.

The top consists of a disk of cardboard about $4\frac{1}{4}$ in. (10·8 cm.) in diameter, mounted upon a spindle. One half of the disk is painted black; upon the white ground of the other half are drawn four successive groups of three black lines, having the form of concentric arcs of 45°, which are at different distances from the centre, as shown in the annexed figure; the thickness of the lines is about $\frac{1}{25}$ in. (1 mm.). When the disk rotates, each group of black lines generally appears to assume a different colour.

The nature of the colours thus developed depends upon the speed of the rotation, and upon the quality and intensity of the illumination. After several trials, I found that no better results, on the whole, could be obtained than when the disk was illuminated by a 16-candle power incandescent lamp, with a ground glass bulb, at a distance of about 6 in. (15 cm.), and was caused to turn about five times in a second. These, therefore, were adopted as the standard conditions for my experiments, the disk being mounted upon a horizontal axis, driven by an electro-motor, and the speed regulated by comparison with the ticks of an ordinary watch.

When the disk rotates under the specified conditions and in the direction indicated by the arrow in the figure, the inner group of



Benham's Top.

lines appears, to my vision, to become bright red, the next group pinkish-brown, the next a dilute olive-green, and the outer group dark blue. If the direction of rotation is reversed, the order of the colours is also reversed.

By far the most striking of these several hues is the first named; hardly any one has the slightest hesitation in pronouncing it to be bright red. As to the blue, there is very rarely any difference of opinion, though it has sometimes been called bluish-green. The hues of the two intermediate groups are much more undecided and difficult to specify, especially when they are seen separately.

The only serious attempts that I know of to explain the origin of the colours shown by the top are those of Professor Liveing and of Captain Abney.* Professor Liveing's explanation is based upon the two hypotheses that the eye perceives certain of the coloured constituents of white light more quickly than others, red being the first to show itself, and that the duration of the impressions due to the different constituents also differs, blue being the last to disappear. Captain Abney thinks that the results would be sufficiently accounted for if the order of persistence of the three colour sensations were violet, green, and red.

Several objections might be urged against these explanations, but the adequacy of either of them seems to be conclusively negatived by

* 'Nature,' vol. 51, pp. 167, 292.

the fact that if the thickness of the lines on the disk is much greater than 1 mm., or, more accurately, if it subtends at the eye a greater angle than about one-fifth of a degree, the red and some of the other colours appear only upon the borders of the lines, their inner portions remaining black or grey.

The true solution, at least as regards the red and the blue, is, I think, to be looked for in certain phenomena attending sudden changes of illumination, which, so far as I have been able to ascertain, have not hitherto been observed.

The following are a few out of a large number of experiments that have been made during the last four months. They are described, as far as possible, in logical and not in chronological order. Persons unaccustomed to visual observations will not easily perceive some of the effects mentioned.

Experiment I.

A circular aperture $\frac{1}{2}$ in. (1·3 cm.) in diameter was made in a sheet of blackened zinc and was covered with thin white writing paper. Diametrically across the aperture a strip of tinfoil $\frac{1}{25}$ in. (1 mm.) wide was attached to the paper. The aperture was closed by a shutter, which could be very rapidly opened by means of a strong spring. The sheet of metal was placed over a window in one side of a light-tight box, inside which at a distance of 1 ft. (30 cm.) from the aperture was an incandescent lamp of 8-candle power with a ground glass bulb. The observations were made at a distance of about 1 ft. from the box, the room being in darkness.

When the shutter was suddenly opened, several curious phenomena appeared simultaneously. The period of their duration was difficult to estimate; it was probably more than one-twentieth of a second and less than one-tenth.

(1) Immediately after it was revealed, the small luminous disk first increased in size with extreme rapidity, and afterwards became somewhat smaller, being in its final condition still larger than at the moment of exposure. This effect was more easily seen when the tinfoil strip was looked at: it seemed to become at first much thinner, then thicker again.

(2) At the moment when the disk was uncovered, a luminous halo, like a broad ring, appeared to start from its margin and spread outwards through a distance of more than an inch (2·5 cm.) in every direction; then it rapidly contracted and disappeared. The halo was blue or blue-violet in colour, and seemed more sharply defined upon its inner than upon its outer border.

(3) Contemporaneously with the existence of the halo, the disk was surrounded by a bright red corona, which, like the halo, expanded outwards, and then contracted. There was not, however,

at any stage a dark interval between the corona and the disk; more probably the inner edge of the corona was slightly within the apparent permanent boundary of the disk. The red corona was very narrow; its greatest width appeared to be rather less than 1 mm., or about one-fifth of a degree. The effect was best seen when the attention was directed upon the tinfoil strip, which for a moment, after the exposure, became bright red, the coronæ, or red borders, of the adjoining semi-disks meeting or perhaps overlapping one another. The apparent temporary excess of the area of the disk above its final area, as mentioned in (1), was probably due to the evanescent red border.*

It is remarkable that repeated experiments had been made with this and similar apparatus for several weeks before the existence of the red border was detected, even though something of the kind was looked for. The difficulty is, not to see it, but to know that one sees it; when once it has been perceived it becomes very conspicuous. The phenomenon is beyond doubt constantly met with, and habitually ignored, in daily life. Since my first observation of it I have many times noticed flashes of red upon the black letters of a book or upon the edges of the page; bright metallic or polished objects often show it when they pass across the field of vision in consequence of a movement of the eyes, and it was an accidental observation of this kind that suggested the following experiment.

Experiment II.

(1) The zinc plate of the last experiment was taken from the box, and the aperture in the plate was covered with thin paper. A ground glass lamp of 8-candle power, attached to a flexible cord, was put behind it, and the whole was moved rather quickly either backwards and forwards or round and round in a small circle at a distance of a foot or so from the eyes. The edges of the straight or circular streak of light thus formed were bordered with red.

(2) A 16-candle power lamp was substituted for the other. The red border then appeared to have a greenish-blue band inside it, slightly encroaching upon the streak of light; probably, however, it was only the apparent or irradiation boundary that was thus affected, not the true geometrical boundary.

(3) The paper was removed, and the 8-candle power ground-glass lamp was again placed behind the aperture. The red could now no longer be seen, but the greenish-blue border remained.

(4) When the 16-candle power lamp was used in the same way

* The effect may be seen without the use of the spring shutter, if a black screen be held before the eyes and suddenly removed, but it is more difficult to hit upon the exact position of the disk.

without any intervening paper, no coloured border could be seen, owing, as it seemed, to the glare.

Experiment III.

The aperture in the metal plate was again covered with white paper, having a strip of tinfoil across it, and the plate was fixed before the window in the box, as in Experiment I; a 16-candle power lamp was placed immediately behind it. When the lamp was switched on, the red border was distinctly seen to be backed with greenish-blue, the red itself being much less evident than when the lamp was 18 in. (45 cm.) behind the aperture.

I have hitherto failed to detect any greenish-blue near the border when the disk was suddenly illuminated by the shutter method of Experiment I, instead of by switching on the lamp.*

Experiment IV.

The object of this experiment was to ascertain whether the red border could be produced by the sudden accession of light which contained no red constituent. Ten different coloured glasses were successively interposed between the lamp and the aperture with the shutter. In every case when the spectroscope showed that the glass transmitted red light, the tinfoil strip became red, but never otherwise. For example, it reddened with a dark blue cobalt glass, but not with a blue glass which transmitted much more light, but intercepted the red end of the spectrum.

Experiment V.

The momentary redness around the edge of the suddenly illuminated disk and along the tinfoil strip, as described in the account of the previous experiments, can only be seen by a practised observer. By a different method, however, it can be made quite evident to almost any person whose vision is normal.

The paper-covered aperture in the box was arranged as before, but the shutter was not used. An incandescent lamp was placed inside the box, and a second lamp outside, at a distance of a few inches from the aperture, the observer's eyes being shaded from it by a screen. The tinfoil strip was on the interior side of the paper, and nothing was seen of it from outside, except when the lamp in the box was alight.

A rotating commutator was constructed, by means of which

* [Since this was written, I have found that the greenish-blue may be shown by the shutter method without difficulty if the distance of the lamp from the aperture is suitably adjusted.—Dec. 19.]

current could be supplied to the two electric lamps in the following manner :—During half a turn of the commutator, no current to either lamp; during the succeeding one-sixth of a turn, current to the interior lamp only; during the remaining one-third of a complete turn, current to the exterior lamp only.

Starting with darkness, and turning the commutator quickly through 180°, the observer saw, as soon as the interior lamp was lighted, the shadow of the tinfoil, which was, as usual at the initial stage, of a bright red hue; but a small fraction of a second later, before it had time to lose its redness and become black, the image was obliterated by a flood of light from the exterior lamp, while at the same moment the other lamp was extinguished.

When the commutator was caused to make four or five turns per second, the image of the tinfoil was almost continuous, and was at once recognised by inexperienced observers to be red.*

This experiment was repeated in another form, the arrangement being such that the light of two lamps was interrupted by screening, instead of by breaking the current; the changes in the illumination could thus be made more rapidly.

Two black cardboard disks, from each of which a sector of 60° had been cut out, were mounted $3\frac{1}{2}$ in. (9 cm.) apart at the ends of a horizontal axle, being so fixed that the posterior edge of the opening in one of the disks was exactly opposite to the anterior edge of that in the other. Between the disks, and in a parallel plane, was suspended a sheet of white paper, across the middle of which a narrow strip of tinfoil was gummed. Two clear glass electric lamps were placed near the outer faces of the disks at the same height as the axis, the incandescent filaments being directed horizontally. To an observer looking at the plain side of the paper across the edge of one of the disks, while they were rotating slowly in the proper direction, the paper first appeared dark all over, then it was illuminated from behind by one of the lamps, the dark strip becoming visible; finally, it was illuminated from the front by the other lamp, and the strip could no longer be seen. When the angular velocity was sufficiently increased, the strip was seen continuously, or nearly so, and its colour was, as before, bright red.

Experiment VI.

From a disk of white cardboard 6 in. (15 cm.) in diameter a sector of 60° was cut out; the remainder of the disk was divided into two

* The lamps used in this experiment were made to my order. They are of 8-candle power and have very thin filaments, the efficiency being 2·5 watts per c.p. They were worked at a pressure of 6 per cent. above their marked voltage, and the incandescence responded very quickly to the current.

equal parts by a straight line from the centre to the circumference, and one of these parts was painted black. The disk was attached to a horizontal spindle, turned by a motor at the rate of five or six revolutions per second, while its front was illuminated by a lamp of 16-candle power. A white card, upon which was a black line, or a design composed of black lines, was supported behind the disk, and viewed intermittently through the open sector. When the rotation was such that the open sector succeeded the black portion of the disk and was succeeded by the white portion, the black lines became red.

This experiment is identical with the last, except that the white ground is illuminated entirely by reflected light. In conjunction with the others, it indicates with certainty the origin of the remarkable red colour shown by Benham's top.

The disk with the open sector affords a much more convenient means than the top of exhibiting the colour phenomena. If a disk with an open sector of 45° or 60° is made of white cardboard, and a movable black half disk is mounted in front of it upon the same axis, we may, by suitably adjusting the position of the black half disk with regard to the opening, produce in a fixed object all the tints shown by the top, as well as intermediate ones; and the object itself may be easily changed to suit the conditions of an experiment.

Experiment VII.

If the commutator of Experiment V, or the disk with the open sector of Experiment VI, be turned in the reverse direction, the strips of tinfoil or the black lines appear to become blue (instead of red), like the outer group of lines in Benham's top when it spins in the direction indicated by the arrow in the figure. This appearance is partly, if not altogether, illusory. It is the bright ground in the immediate neighbourhood of the black lines that becomes blue; the lines themselves (except possibly just within their extreme edges) become a neutral grey, owing to the alternations of light and darkness or of white and black.

A card with some black lines 1 mm. thick drawn upon it was placed behind the disk with the open sector of Experiment VI, which was turned in the direction such that the open sector was preceded by white and followed by black. The lines presented the appearance of having been drawn with blue ink upon imperfectly sized paper, a blue stain having apparently spread for a short distance on both sides of the lines.

Lines of gradually increased thickness were successively employed until at last they had the form of bands $\frac{3}{8}$-in. wide; and even in this latter case it was not easy to see that the bands themselves did not become blue, but only their outlying borders.

When, however, a visiting card which had been blackened over its whole surface was placed behind the rotating disk, it merely turned a lighter black, or rather grey, in which it was impossible to imagine the slightest tinge of blue.

A small piece of white paper which was subsequently attached to the middle of the card became blue around its edges when the disk was turned, but the blue did not encroach at all (or if at all, only to a very small extent) upon the black ground.

When these observations have been made it becomes possible to recognise that the apparently blue lines in the top are themselves really grey, and only bordered externally with blue.

Experiment VIII.

The natural conclusion from the observations described above is that if a black disk were suddenly formed upon a bright ground, the disk would for a moment appear to be surrounded by a blue border. I was not successful in devising a satisfactory arrangement for suddenly creating a black disk, but the effect is sufficiently shown in the following manner.

An aperture $1\frac{1}{4}$ in. (3 cm.) in diameter was cut in one side of a wooden box and was covered with white paper; one half of the aperture could be suddenly covered by a sliding metal shutter which was actuated by a spring: a lamp was placed inside the box. When the shutter was operated, a blue band 1 or 2 mm. wide appeared on the bright ground just beyond and adjoining the edge of the shutter when at rest. Its duration was thought to be slightly longer than that of the red border of other experiments, and it appearently disappeared by retreating into the black edge of the shutter.

When the shutter was moved by hand across the field at a slower speed, its edge was seen to be preceded by a thin blue border, which, when the shutter reached its limiting stop, appeared to reverse the direction of its motion and return into the shutter.

The blue border is much less conspicuous and more difficult of observation than the red one. In order to see it plainly careful adjustment of the light is necessary. An examination of the effect through coloured glasses was attended by uncertain results.

Remarks on the Experiments.

The phenomenon which in the account of Experiment I has been spoken of as a blue halo may be due either to a momentary sympathetic excitement of the nerve fibres of the retina in the neighbourhood of those directly acted upon by the light, or, as I think, less probably, to light scattered by the imperfectly transparent media of the eye. In the latter case its rapid disappearance might be accounted for

partly by the diminished sensibility of the retina after the first moment and partly by the contraction of the iris. The dark interior of the halo, which begins to appear soon after its formation, is probably connected with a class of visual sensations which have been specially studied by M. Aug. Charpentier.* The sensation of luminosity is followed very shortly after its first excitment by a brief, dark reaction, and it is perhaps the momentary revival of the luminosity after this reaction that gives the halo the appearance of retreating into the bright disk.

But whatever the cause of the halo, there can hardly be any doubt that the corona or narrow red border is due to sympathetic excitation. When the red nerve-fibres of the Young-Helmholtz theory are affected by light the intensity of which does not exceed a certain limit, the immediately surrounding red nerve-fibres are for a short period sympathetically affected, while the violet and green are not so, or in a much less degree.

It must be confessed that it is more difficult to offer a reasonably simple explanation of what happens when the intensity of the light exceeds the limit above indicated, and the band of greenish-blue consequently appears in addition to, or in place of, the red border. It is, perhaps, preferable to refrain at present from any speculation on the subject.

When a Benham's top is spun in bright daylight or weak sunshine, it is quite possible to distinguish both the red and the greenish-blue at the same time, the latter encroaching somewhat upon the white ground; its persistence is greater than that of the red, as can easily be seen when the top is turning rather slowly. The greenish-blue appears to be of the hue that is complementary to red, and it is evidently the development of this colour that makes the red so much less conspicuous when the top is illuminated by daylight than when artificial light is employed.

The obvious method of accounting for the formation of the blue border around a patch in a bright field from which light has suddenly been cut off, is to suppose a brief sympathetic reaction in the nerve-fibres adjacent to those from which the exciting stimulus has been withdrawn, this reaction being more marked in the red fibres than in the green and violet, or perhaps occurring in the red fibres only, at least when the light is of the usual intensity. If the red fibres just outside the darkened patch ceased for a moment to respond to the luminous stimulus, in sympathy with those inside the patch, the appearance of a blue border would be produced.

In sunlight I have sometimes found that the lines in Benham's top which ordinarily appear blue, assumed a reddish colour; under

* 'Comptes Rendus,' vol. 113 (1891), p. 147.

strong illumination therefore the sympathetic dark reaction would seem to be least in the case of the red fibres.

Subjective colours of the same class as those shown by Benham's top, but not nearly so conspicuous, have long been known. Helmholtz* mentions that if a rotating disk with black and white sectors is looked at fixedly, each white sector appears to be reddish along its leading border and bluish along its rear border. He also remarks that these colours are more easily seen upon a disk covered with two spiral bands, black and white, of equal breadth. From these and other observations, Helmholtz concludes that when a point of the retina is exposed to rapid alternations of white light and of darkness, causing successive states of increasing and decreasing excitation, the moment of maximum excitation is not the same for all colours. It has, however, been shown above that in analogous cases the red originates in a portion of the retina which has not been exposed to the direct action of light, while the blue originates in a portion where light has not ceased to act. Helmholtz's supposition therefore does not apply—at least to the class of colours at present under consideration.

I have not made any attempt to account for the more feeble colours exhibited by the two intermediate groups of lines in Benham's top, nor for the changes which occur when the speed of rotation is increased. These effects no doubt result, at least in part, from modifications of the phenomena already discussed. But for the present I am compelled to discontinue the experiments on account of the disagreeable and probably injurious effects which they produce upon the eyes.

"On the Effect of Pressure in the Surrounding Gas on the Temperature of the Crater of an Electric Arc. Correction of Results in former Paper." By W. E. WILSON, F.R.S., and G. F. FITZGERALD, F.R.S. Received November 30,—Read December 17, 1896.

In May, 1895, a preliminary paper by one of the authors was read at the Royal Society, in which is described the apparatus used for these experiments, and the results which were then obtained.

The primary object of this research was to determine, if possible, whether the temperature of the crater in the positive carbon varies when the pressure in the surrounding gas is changed.

It has been suggested that the temperature of the crater is that of

* 'Phys. Optik,' § 23.